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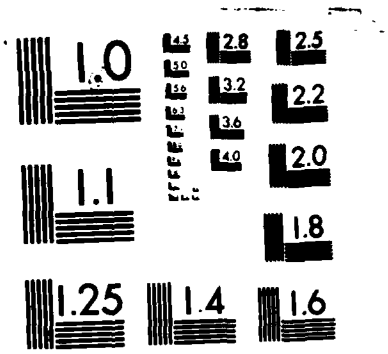

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Princeton University

FINAL REPORT
AFOSR Grant 84-0061

"Study of Longitudinal Curvature Effects in Turbulent Boundary Layers, with Application to Drag Reduction"

by

A. J. Smits

MAE Report 1725
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This work was concerned with a study of subsonic boundary layer behavior downstream of a 90 degree convex bend with a boundary layer thickness of radius-of-curvature ratio of approximately 0.1. Only mean flow results are available. They indicate that the boundary layer, severly distorted when it exits from the curved region, experiences several stages in the recovery process as it relaxes on the flat plate. These stages are described in detail in the report.

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1. INTRODUCTION

This report is the Final Technical Report on AFOSR Grant 84-0061, monitored by Drs. M. Francis and J. McMichael. The report describes experimental work on longitudinal curvature effects in turbulent boundary layers performed in the Department of Mechanical and Aerospace Engineering of Princeton University during the period February 15, 1984 to February 14, 1985.

The effect of curvature on boundary layer behavior is of great fundamental and practical interest. In particular, the impulsive application of convex curvature reduces viscous drag, and the rate of recovery of the boundary layer downstream is therefore important because of the implications for drag reduction.

The current report summarizes the work performed with the support of Grant 84-0061. This work was principally concerned with a study of subsonic boundary layer behavior downstream of a 90° convex bend with a boundary-layer thickness to radius-of-curvature ratio of approximately 0.1. The preliminary work required to set up the experiment is described in Section 2, and the experimental results are summarized in Section 3. Some additional work was performed as preparation for extending this investigation to supersonic flow. This work is described in Section 4. Further details, such as a description of the test facility, and a list of publications produced under the sponsorship of this grant, are given in the Appendices.

2. PRELIMINARY WORK

The existing wind tunnel (described in Appendix A) was extensively modified for the experiment. Firstly, a considerable amount of work was performed to improve the quality of the incoming boundary layer. Initial testing revealed that the existing inlet section produced spanwise skin friction variations of up to 16% (see Fig. 2). The magnitude of these variations was completely unacceptable, particularly because any pre-existing spanwise variations would be considerably amplified in the concavely curved region. A number of modifications were implemented including new screens and altering the contraction. The final peak-to-peak variations, shown in Fig. 3, are everywhere less than 4%. We believe this level to be acceptable.

Secondly, the three convex bends were designed (30°, 60° and 90°). The outer wall shapes were designed using an inviscid Laplace solver to minimize the pressure gradients on the inner test wall. To keep the boundary layer on the outer wall attached, suction was applied along a slot in the region of maximum pressure gradient. The inner and outer walls were constructed, and the suction system was extensively tested.

Thirdly, the downstream test wall was modified to accept a standardized probe mounting system. This system considerably simplifies data taking procedures.

Fourthly, software appropriate for subsonic single and crossed hot-wire anemometry was developed and tested.

3. EXPERIMENTAL WORK

The experimental arrangement is shown in Fig. 4. An incompressible turbulent boundary layer, U_e = 23 m/sec, grows over a 1.5 m flat plate before being turned over a convex surface. At the entrance to the curvature, $\delta/R \sim 0.1$ and $Re_\theta \sim$ 4700. Through the bend, the boundary layer experiences a modest pressure gradient (see Fig. 5). After the curvature, the boundary layer recovers on a 4.6 m flat plate ($\sim 120\delta$).

At present, only mean flow results from the 90 degree bend case are available. They indicate that the boundary layer, severely distorted when it exits from the curved region, experiences several stages in the recovery process as it relaxes on the flat plate. This recovery pattern is shown by the skin friction, the shape factor, the extent of the wall region, and the wake factor. In the first stage, these parameters undergo a sudden increase at the exit to curvature and recover approximately halfway to their flat plate values in a distance of 10δ. The second stage is a continuation of this trend, although the changes are less pronounced and occur over a much longer distance. However, the recovery does not asymptotically approach the flat plate state; instead, the boundary layer "over-recovers" after about 60δ. This third stage shows no sign of reversal after 120δ.

These stages are demonstrated in Figs. 6 and 7. Figure 6 shows the skin friction as a percent of the value predicted by

a flat plate correlation based on distance from the virtual origin. At the second measuring station, 2δ after the curved region, the skin friction is 45% of its equivalent flat plate value. At the next measuring station, 5δ farther downstream, the skin friction has increased to 70% of this reference value. Subsequently, the recovery rate decreases with streamwise position, and 65δ after the end of curvature, the measured skin friction agrees with the predicted value. After this point the skin friction continues to increase and eventually overshoots the flat plate value by 15% at a point 120δ downstream of the end of curvature.

Figure 7 shows some selected velocity profiles plotted in wall coordinates. The upstream profile indicates a standard flat plate boundary layer, in terms of both the wake factor (2.8) and the extend of the wall region ($y+ \sim 250$). At the first measuring station downstream of the curved wall, the profile is markedly distorted: the wake factor has increased to 17.2 and the wall region ends at $y+ \sim 90$. The next profile clearly shows the fast recovery. Here, the wake factor drops to 9.0 and the wall region extends to 150 wall units. The last profile demonstrates the "over-recovery", and the wall region extends beyond $y+ = 1000$ as the wake factor drops to its minimum value of 1.2.

It is not yet known whether this "over-recovery" represents some new equilibrium condition, or whether the mean flow parameters are demonstrating underdamped second order behavior

before eventually returning to standard flat plate levels. Turbulence measurements should shed some light on this question; in particular, they will tell us whether the "active" layer mentioned above has filled out the whole boundary layer after 120δ. These turbulence measurements are currently being taken with support from AFOSR Grant 85-0126.

4. ADDITIONAL WORK

It is the intention of this research program to extend the study of curvature effects to boundary layers in supersonic flow. To study the turbulence behavior, we intend to use constant-temperature hot-wire anemometry. However, our previous measurements in supersonic turbulent boundary layers were considered accurate only if the local Mach number, or the normal Mach number component (in the case of inclined wires), was greater than 1.2.

To extend our measurement range, a test program was conducted to study the transonic response of constant temperature hot-wires. By direct calibration in a variable density blow-down wind tunnel, the wire sensitivities to mass-flow rate and density were found as a function of Mach number. Mach numbers were varied from 0.5 to 1.4, and the wire Reynolds numbers ranged from 100 to 300.

It was found that within these test conditions, the mass-flow rate and density sensitivities were almost equal and essentially independent of Mach number and Reynolds number. Hence, this study showed that our normal wire turbulence measurements near the wall are not significantly effected by transonic effects. Inclined wires were also tested but the results are still being analyzed and no conclusions are currently available.

In further additional work, the Principal Investigator has written two review articles (1) "The Response of Turbulent Boundary Layers to Sudden Perturbations," with D. H. Wood, Annual Review of Fluid Mechanics, 17:321-58, 1985, and (2) "The Control of Turbulent Boundary Layers by the Application of Extra Strain Rates," AIAA Paper #85-0538, AIAA Shear Flow Control Conference, Boulder, Colorado, March 1985.

These articles were stimulated at least in part by the Principal Investigator's commitment to AFOSR under Grant 81-0061, and they therefore carry an appropriate acknowledgement.

APPENDIX A

Measurements were taken in the new subsonic wind tunnel, located at the Gas Dynamics Laboratory, Forrestal Campus. This tunnel is of the open- return suction type, and is powered by a two speed, 10 H.P. fan. The outlet from the 6:1 contraction has a rectangular cross-section of 6" x 48" (150mm x 120mm) and exit velocities of approximately 23 m/s and 34 m/s. One of the 48" wide vertical sides is used as a test wall.

The tunnel has been modified to incorporate a short, convexly curved bend of either 30°, 60° or 90° turning angle. The outer wall of the bend is designed to minimize the pressure gradients on the inner test wall, and suction is provided to keep the outer wall boundary layer attached. The upstream boundary layer develops in a zero pressure gradient until low Reynolds number effects are negligible ($R_\theta > 4000$), and the 99% thickness is approximately 25 mm (at a freestream velocity of 23 m/s). Downstream of the curved section, there is a 4.6 m long working section with an adjustable outer wall, used to minimize the pressure gradients in the recovery zone (see Fig. 4).

APPENDIX B

Publications produced with the support of AFOSR Grant 81-0061

Smits, A. J. and Wood, D. H., "The response of turbulent boundary layers to sudden perturbations," Annual Review of Fluid Mechanics, 1985, 17:321-58.

Smits, A. J., "The control of turbulent boundary layers by the application of extra strain rates," AIAA Paper 85-0538, AIAA Shear Flow Control Conference, March 1985, Boulder, Colorado.

Rong, B. S., Tan, D.K.M. and Smits, A. J., "Calibration of the constant temperature normal hot-wire anemometer in transonic flow," Princeton University, Dept. of Mechanical & Aerospace Engineering, Report MAE-1696, April 1985.

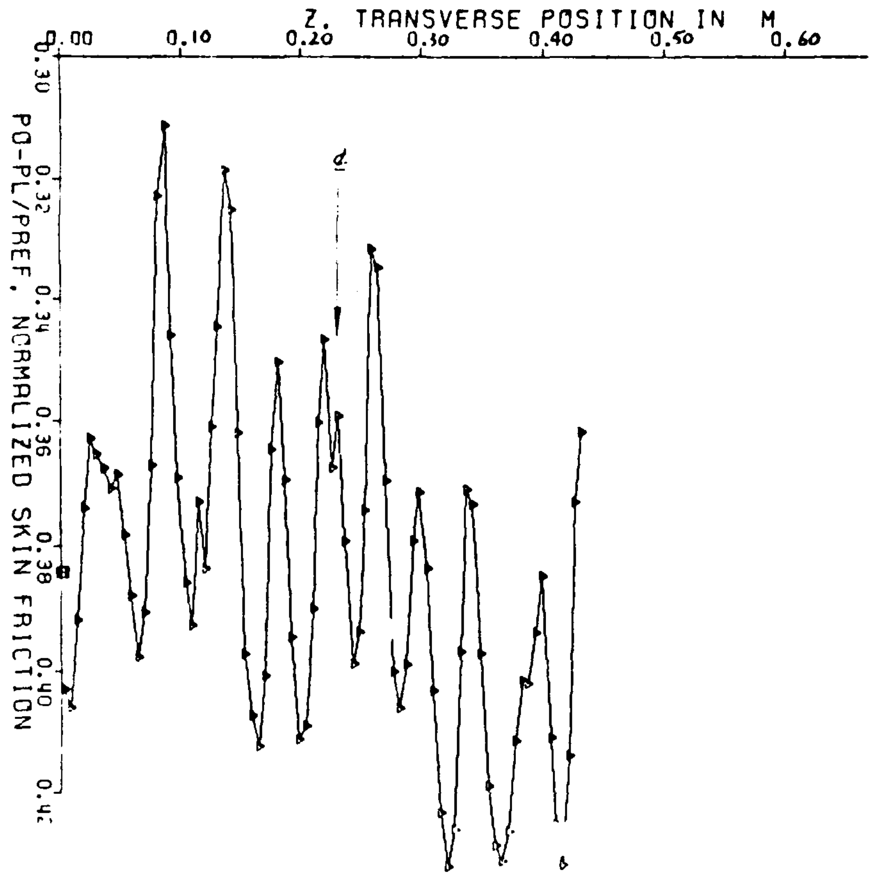

Fig. 1. Original spanwise skin friction distribution (Metal screens $\beta = 0.56$, where β = open area/total area

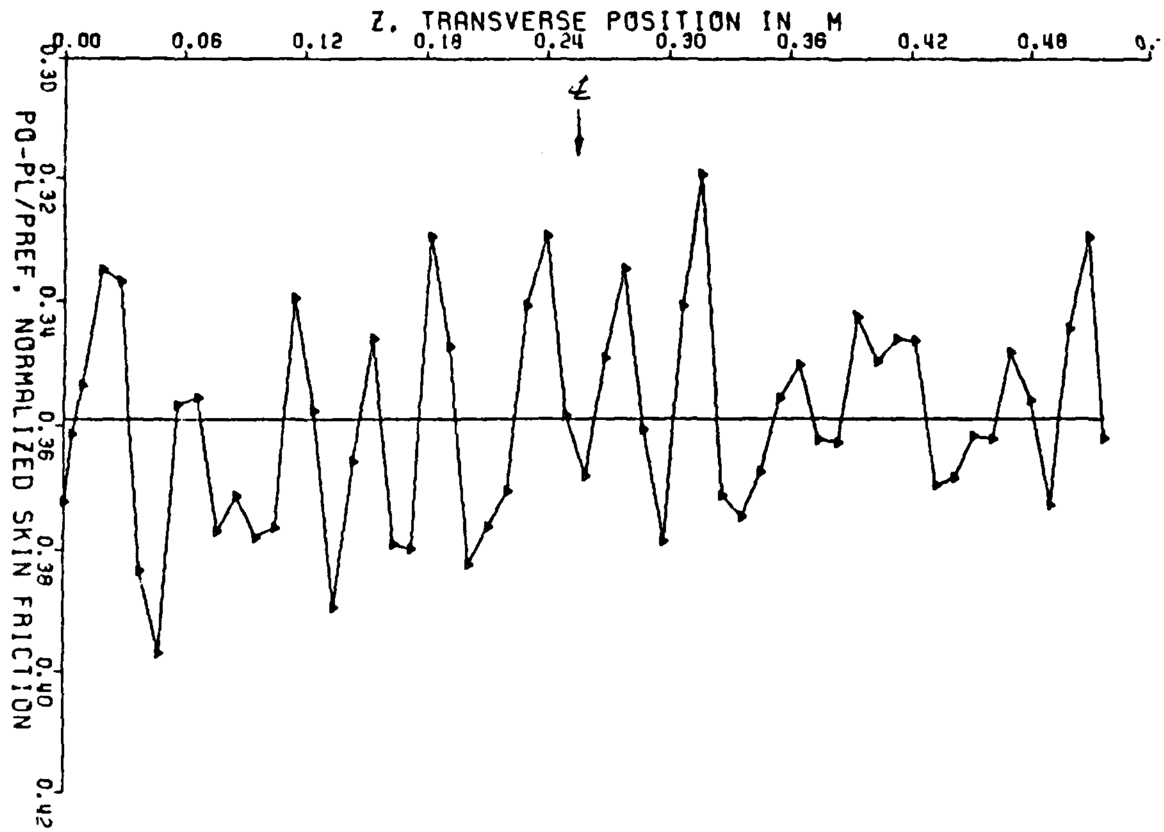

Fig. 2. First attempt to improve spanwise distribution (Fiberglass screens β =0.80)

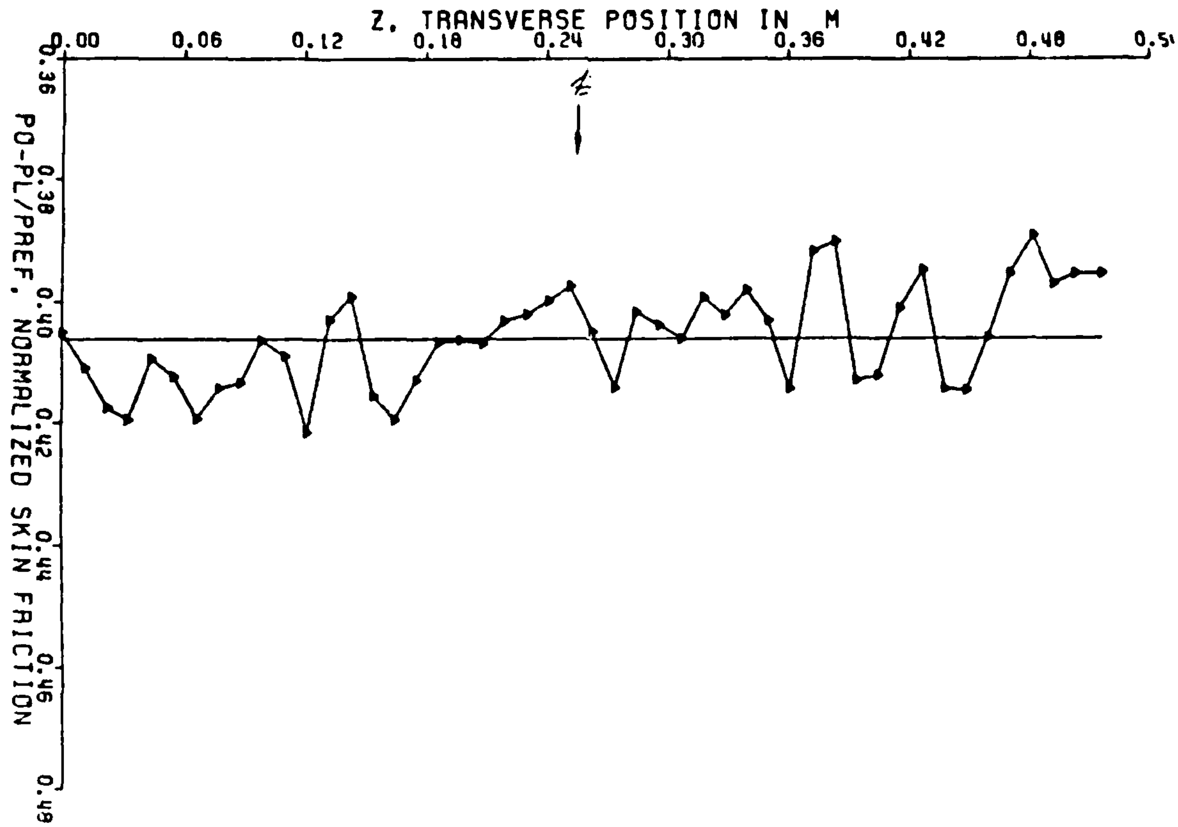

Fig. 3. Final skin friction distribution ± 25cm of centerline (Metal screens β = 0.67 and β = 0.63)

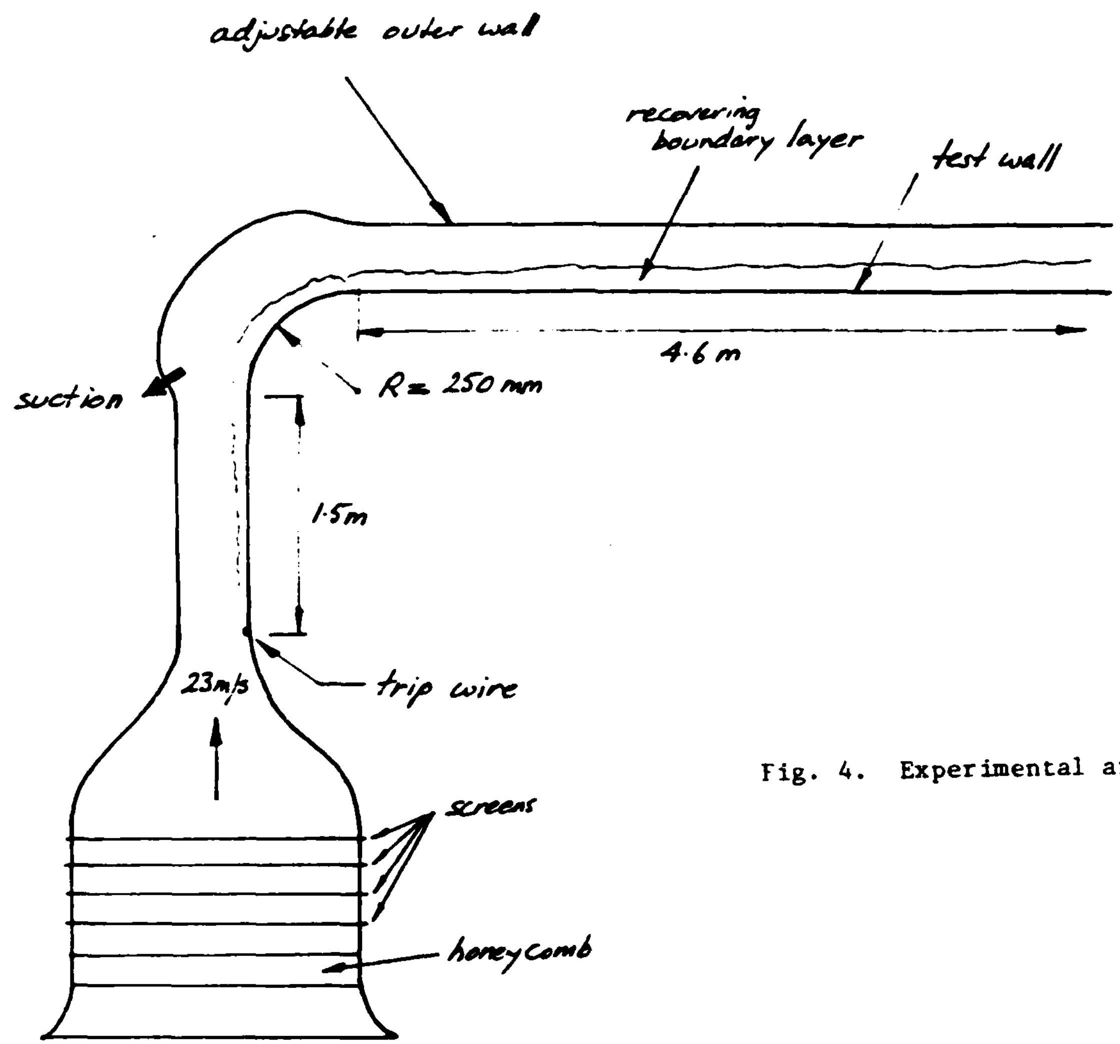

Fig. 4. Experimental arrangement

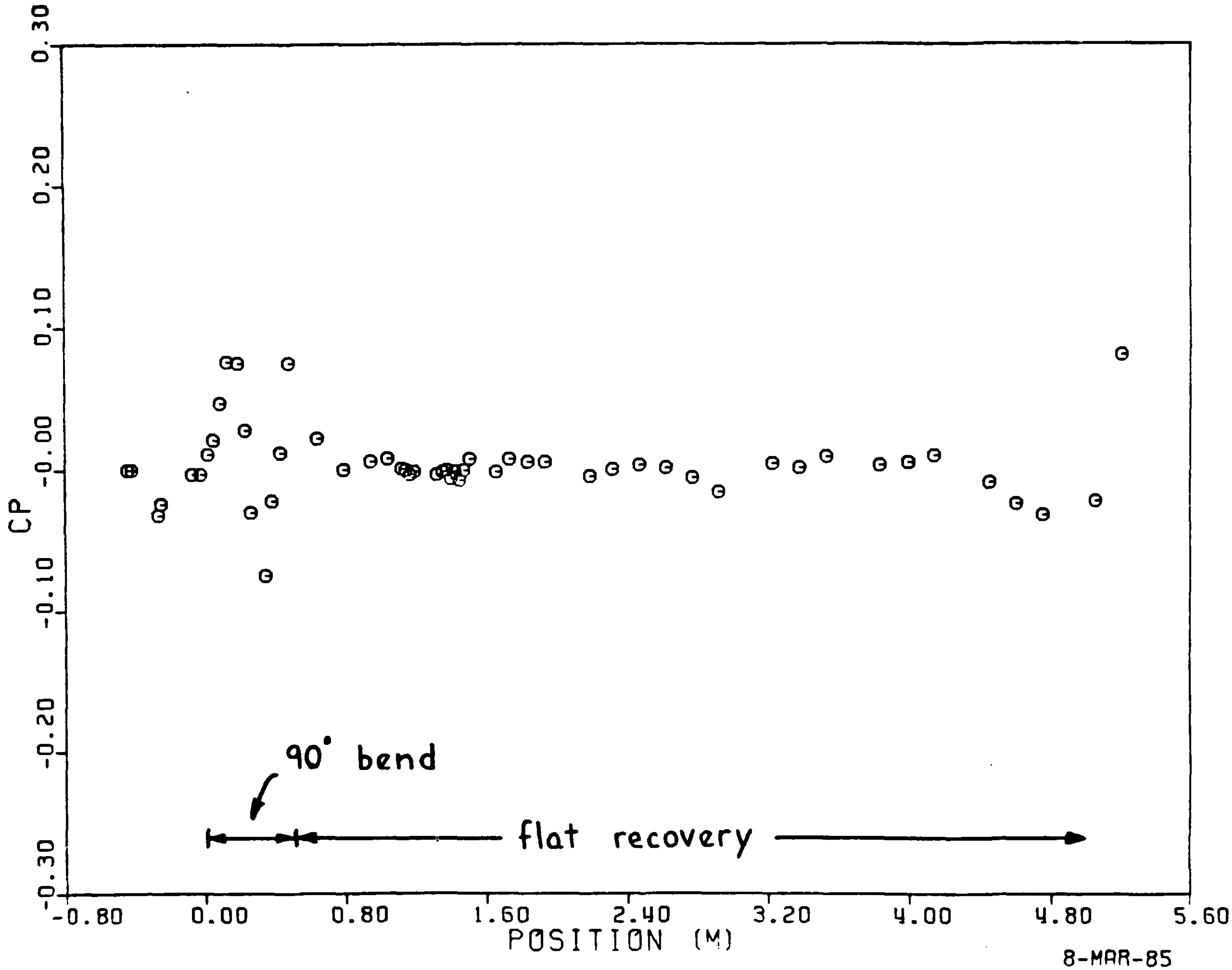

Figure 5. Streamwise static pressure coefficient.

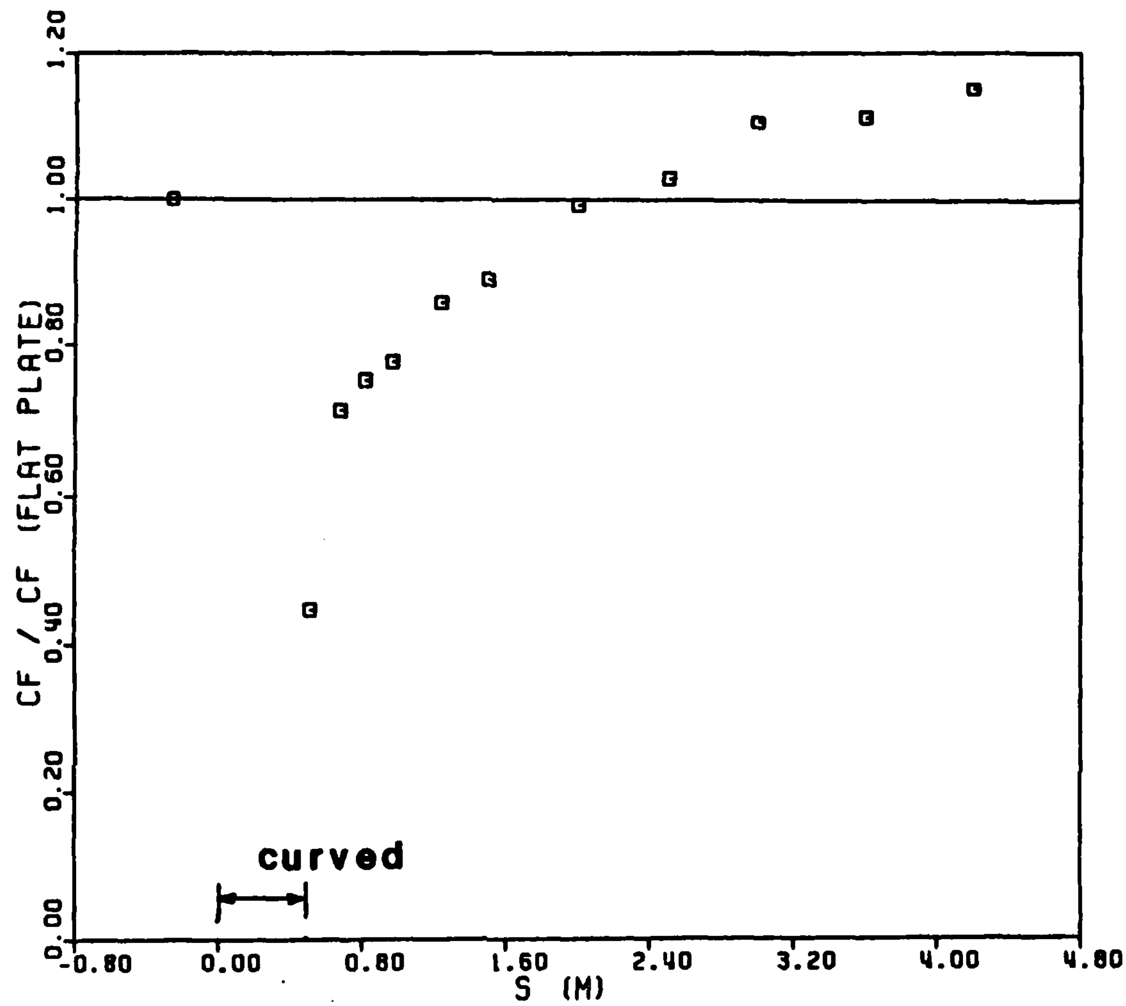

Fig. 6. Distribution of skin-friction coefficient normalized by the flat-plate value at the same Reynolds number based on momentum thickness.

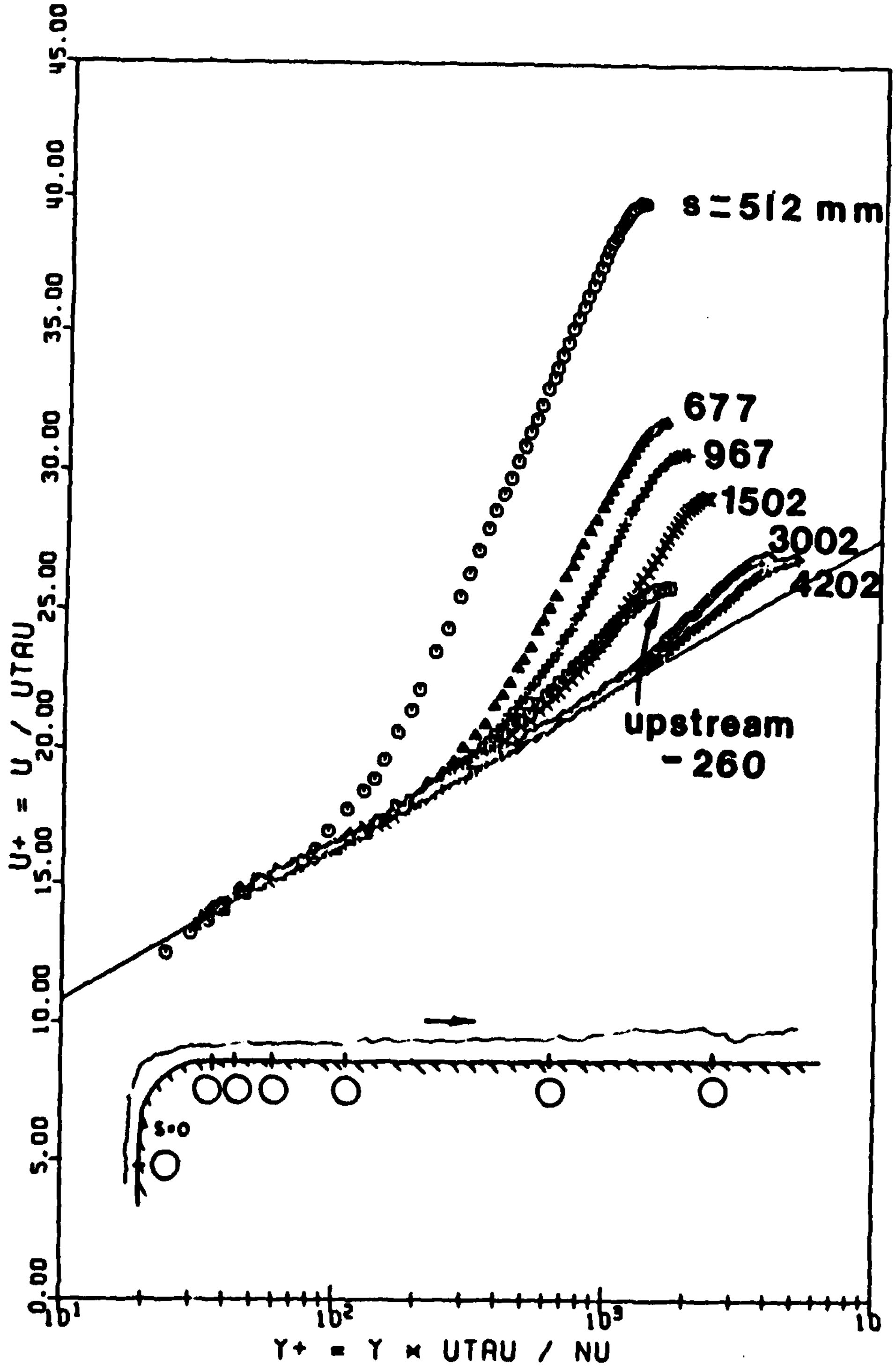

Fig. 7. Velocity profiles in the recovery zone shown in semi-log coordinates.

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